Remote Sensing in Ecology and Conservation
Open Access
ZSL
LET'S WORK
FOR WILDLIFE

POLICY FORUM

Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward

Nathalie Pettorelli[1], Henrike Schulte to Bühne[1], Ayesha Tulloch[2], Grégoire Dubois[3], Cate Macinnis-Ng[4], Ana M. Queirós[5], David A. Keith[6,7,8], Martin Wegmann[9], Franziska Schrodt[10], Marion Stellmes[11], Ruth Sonnenschein[12], Gary N. Geller[13,14], Shovonlal Roy[15], Ben Somers[16], Nicholas Murray[6], Lucie Bland[17], Ilse Geijzendorffer[18], Jeremy T. Kerr[19], Stefanie Broszeit[5], Pedro J. Leitão[20,21], Clare Duncan[17], Ghada El Serafy[22], Kate S. He[23], Julia L. Blanchard[24], Richard Lucas[25], Paola Mairota[26], Thomas J. Webb[27] & Emily Nicholson[17]

[1]Institute of Zoology, Zoological Society of London, Regent's Park, NW1 4RY London, UK
[2]School of Earth and Environmental Sciences, University of Queensland, Brisbane, 4072 Qld., Australia
[3]European Commission, Joint Research Centre (JRC), Directorate D – Sustainable Resources, via E. Fermi 2749, I-21027 Ispra, VA, Italy
[4]School of Biological Sciences, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[5]Plymouth Marine Laboratory, Prospect Place, PL1 3Dh Plymouth, UK
[6]Centre for Ecosystem Science, School of Biological, Earth and Environmental Science, University of New South Wales, Kensington, NSW 2052, Australia
[7]NSW Office of Environment and Heritage, Hurstville, NSW 2220, Australia
[8]Long Term Ecological Research Network, Terrestrial Ecosystem Research Network, Australian National University, Canberra, ACT 0200, Australia
[9]Department of Remote Sensing, Ecology and Conservation Research, Institute of Geography and Geology, University of Würzburg, Würzburg, Germany
[10]School of Geography, University of Nottingham, Nottingham NG7 2RD, UK
[11]Remote Sensing and Geoinformatics, Institute of Geographical Sciences, Freie Universität Berlin, Malteserstraße 74-100, 12249 Berlin, Germany
[12]Institute for Earth Observation, Eurac Research, Viale Druso 1, Bolzano, Italy
[13]Group on Earth Observations (GEO), Geneva, Switzerland
[14]NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[15]Department of Geography and Environmental Science & School of Agriculture, Policy and Development, University of Reading, Whiteknights, Reading RG6 6AB, UK
[16]Division Forest, Nature and Landscape, KU Leuven, Celestijnenlaan 200E, 3001 Heverlee, Belgium
[17]Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood, Vic. 3121, Australia
[18]Institut de recherche pour la conservation des zones humides méditerranéennes, Le Sambuc, 13 200 Arles, France
[19]Department of Biology, University of Ottawa, Ottawa, ON K1N6N5, Canada
[20]Department Landscape Ecology and Environmental System Analysis, Institute of Geoecology, Technische Universität Braunschweig, Langer Kamp 19c, D-38106 Braunschweig, Germany
[21]Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, D-10099 Berlin, Germany
[22]Marine and Coastal Systems, Deltares, Rotterdamseweg 185, PO Box 177, 2600 MH Delft, The Netherlands
[23]Department of Biological Sciences, Murray State University, Murray, KY, USA
[24]Institute for Marine and Antarctic Studies and Centre for Marine Socioecology, University of Tasmania, 20 Castray Esplanade, Hobart, Tas., Australia
[25]Centre for Ecosystem Science (CES), School of Biological, Earth and Environmental Science (BEES), The University of New South Wales (UNSW), High Street, Kensington, NSW, Australia
[26]Department of Agro-Environmental and Territorial Sciences, University of Bari, "Aldo Moro", Via Orabona 4, 70125 Bari, Italy
[27]Department of Animal & Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK

Keywords
Biodiversity loss, biodiversity monitoring, ecosystem functions, ecosystem services, satellite remote sensing

Correspondence
Nathalie Pettorelli, Institute of Zoology, Zoological Society of London, Regent's Park, NW1 4RY London, UK. Tel: +44 (0)207 449 6334; E-mail: nathalie.pettorelli@ioz.ac.uk

Abstract

Societal, economic and scientific interests in knowing where biodiversity is, how it is faring and what can be done to efficiently mitigate further biodiversity loss and the associated loss of ecosystem services are at an all-time high. So far, however, biodiversity monitoring has primarily focused on structural and compositional features of ecosystems despite growing evidence that ecosystem functions are key to elucidating the mechanisms through which biological diversity generates services to humanity. This monitoring gap can be traced to the current lack of consensus on what exactly

Editor: Marcus Rowcliffe
Associate Editor: Mat Disney

Received: 3 April 2017; Revised: 19 May 2017; Accepted: 23 June 2017

doi: 10.1002/rse2.59

ecosystem functions are and how to track them at scales beyond the site level. This contribution aims to advance the development of a global biodiversity monitoring strategy by proposing the adoption of a set of definitions and a typology for ecosystem functions, and reviewing current opportunities and potential limitations for satellite remote sensing technology to support the monitoring of ecosystem functions worldwide. By clearly defining ecosystem processes, functions and services and their interrelationships, we provide a framework to improve communication between ecologists, land and marine managers, remote sensing specialists and policy makers, thereby addressing a major barrier in the field.

Introduction

Biodiversity is in crisis, as wildlife populations decline (McCauley et al. 2015; WWF Living Planet Report 2016), species extinction rates surge (Ceballos et al. 2015; Alroy 2015; Webb and Mindel 2015), and ecosystems fragment, degrade and collapse (Valiela et al. 2001; Hansen et al. 2013). To halt further depletion of the Earth's biological diversity and avoid detrimental impacts on human well-being (Millennium Ecosystem Assessment 2005), there is an urgent need not only to improve our ability to track changes in biodiversity and the pressures affecting it (Halpern et al. 2008; Pettorelli et al. 2014), but also to further our understanding of the relationships between biodiversity and ecosystem services (Geijzendorffer and Roche 2013; Harrison et al. 2014). Key to elucidating the mechanisms through which biological diversity generates services to humans is the concept of ecosystem functions (Duncan et al. 2015).

What ecosystem functions are and how they relate to biodiversity has been subjects of debate for decades, due partly to much confusion over definitions (Paterson et al. 2012; Roe et al. 2013). Biodiversity, as defined in the seminal paper by Noss (1990), possesses three primary attributes – composition, structure, and function – which can be tracked at multiple levels of biological organization, from ecosystem to population/species and genetic. This definition, which underpins the definition adopted by the United Nations Convention on Biological Diversity (CBD), makes it clear that biodiversity is a fundamentally multidimensional concept that includes ecosystem functions (Culman et al. 2010).

Interestingly, ecosystem functions are rarely measured, particularly over large areas, with biodiversity monitoring as a whole having historically been primarily based on structural and compositional features of the observed systems, rather than functional features (Callicott et al. 1999; Magurran 2004; Schröter et al. 2016). Past attempts to measure ecosystem functions have indeed been primarily undertaken at relatively small spatial extents, and can be grouped into four broad categories, namely: (i) proxy-based monitoring based on population and species data (Drever et al. 2008; Kehinde and Samways 2012), (ii) process-based monitoring (such as using primary productivity to track changes in pollination; Werling et al. 2014), (iii) proxy-based monitoring based on genetic information (such as determining functional connectivity of populations; Braunisch et al. 2010) and (iv) trait-based monitoring [assuming either that high trait or functional diversity is a proxy for good ecosystem functioning (see e.g. Moretti and Legg 2009) or that dominant trait values determine the rates of functions (see e.g. Queirós et al. 2013; Solan et al. 2004)]. Most ecosystem assessments and conservation efforts then fail to account for functions due to a perceived lack of adequate spatial data to map these features (Tulloch et al. 2016), instead relying on species and structural data as surrogates for processes.

This reliance on compositional and structural features to track changes in ecosystem functions, as well as the current inability to map multiple functions across broad scales not only hampers our ability to expand our understanding of biodiversity-ecosystem services relationships, but also hinders the development of conservation management strategies (e.g. no-net loss strategies), impairs environmental impact assessments and limits our comprehension of what sustainable development should take into consideration (Fuhlendorf et al. 2006; Kollmann et al. 2016). Ecosystem functions may indeed sometimes respond more quickly to environmental change than structural or compositional attributes (McNaughton et al. 1989; Milchunas and Lauenroth 1995), and as such, could be among the most sensitive indicators of change when monitoring ecosystems globally (Daily et al. 2009; Haines-Young et al. 2012; Koschke et al. 2012).

Despite extensive discussion of the need for coordinated monitoring of ecosystem functions (Oliver et al. 2015), the practical implementation of such an approach is still lacking. Progress to recognize and fill this biodiversity monitoring gap has, however, been made in the past 10 years. Notably, the Red List of Ecosystems assessments, which are based on a set of criteria for performing evidence-based assessments of the risk of ecosystem collapse, explicitly refer to the monitoring of ecosystem functioning (Keith et al. 2015). However, assessments undertaken thus far have highlighted the relative lack of data on ecosystem functioning, with 50% of them not assessing functional criteria (L. Bland, pers. comm.). In parallel to this, the Group on Earth Observations – Biodiversity Observation Network (GEO BON) developed a framework for biodiversity monitoring based on the concept of essential biodiversity variables (EBVs) (Pereira et al. 2013), which includes a class for ecosystem functions. However, so far no scientific consensus has been reached on what exactly ecosystem functions are and how to track them at scales beyond the site level; this lack of clarity has hampered progress in terms of identifying opportunities for ecosystem function monitoring globally.

To address these gaps, we propose the adoption of a set of definitions and typology for ecosystem functions relevant to both terrestrial and marine ecologists, building on previous efforts to identify and monitor ecosystem functions (Petter et al. 2012; Meyer et al. 2015). Because satellite remote sensing is the only methodology currently able to provide global coverage and continuous measures across space at relatively high spatial and temporal resolutions (Skidmore et al. 2015; Pettorelli et al. 2016), we subsequently provide an up-to-date perspective on the current and future prospects of satellite remote sensing for monitoring ecosystem functions in both the terrestrial and marine realms, reviewing established products, highlighting new developments that have the greatest potential to make a difference to practitioners and policy makers, and discussing potential limitations. We conclude by stressing opportunities for the proposed monitoring framework to inform relevant global policy initiatives.

Agreeing on What Ecosystem Functions Are

Ecosystem processes, ecosystem functions and ecosystem services

Ecosystem functions mean different things to different people. Multiple definitions of ecosystem functions can indeed be found in the literature and the term is often used synonymously with ecosystem services (Srivastava and Vellend 2005; Lamarque et al. 2011), ecological processes (Lawton and Brown 1993) and ecosystem processes (Dominati et al. 2010; Mace et al. 2012; see Table 1). Yet without agreement on what ecosystem functions are (Table 1), progress on our ability to monitor them is likely to be slow and erratic.

To help identify an implementable framework for the monitoring of ecosystem functions globally, we here suggest adopting the following definitions of ecological processes, ecosystem processes, ecosystem functions and ecosystem services, which are applicable across all ecological realms and integrate these concepts into a common framework consistent with Noss' (1990) definition of biodiversity (Fig. 1). Specifically, we considered three criteria to select appropriate definitions of these terms, namely (i) the proposed definitions should clearly separate functional and structural/compositional properties of ecosystems; (ii) they should clearly distinguish between organism- and ecosystem-level properties; and (iii) they must allow integrating all concepts (i.e. ecological processes, ecosystem processes, ecosystem functions and ecosystem services) in a common framework.

An overview of existing definitions of ecological processes, ecosystem processes, ecosystem functions and ecosystem services are provided in Table 1, together with the rationale behind retaining or rejecting a given definition. Based on this approach, we here define *ecological processes* as activities that result from interactions among organisms and between organisms and their environment, following Martinez (1996). Examples of ecological processes thus include competition, herbivory, carnivory and photosynthesis. *Ecosystem processes* are then understood as transfers of energy, material, or organisms among pools in an ecosystem, following the definition introduced by Lovett et al. (2006). Examples of ecosystem processes include primary production, decomposition, heterotrophic respiration and evapotranspiration. Similarly, we propose to adopt the definition of *ecosystem functions* put forward by Lovett et al. (2006), which states that ecosystem functions are attributes related to the performance of an ecosystem that are the consequence of one or multiple ecosystem processes. Specifically, we understand ecosystem functions as the direct and indirect benefits of ecosystem processes for a range of species, including humans. Under this definition, examples of ecosystem functions include nutrient regulation, food production and water supply. *Ecosystem services* are finally defined as the benefits human populations derive, directly or indirectly, from ecosystem functions, following the definition introduced by Costanza et al. (1997). Examples of ecosystem services include food (refers to any nutritious substance that people, and/or other species that people value, eat to maintain life and growth, such as game, fish, crop) production, raw material production (referring here to raw material that people use, such as skin, fuel wood, fodder), carbon sequestration, recreational experience and cultural services. The key distinction between ecosystem functions and services, as noted by Petter et al. (2012), is that functions can have both intrinsic and potential anthropocentric values, while services are defined only in terms of their benefits to people.

Table 1. Coexisting definitions pertinent to the concepts of ecological processes, ecosystem processes, ecosystem functions and ecosystem services.

Concept	Definition	Reference	Benefit/Drawback
Ecological processes	***Activities that result from interactions among organisms and between organisms and their environment***	***Martinez (1996)***	***This definition separates organism level processes from ecosystem level processes***
	An interaction among organisms; ecological processes frequently regulate the dynamics of ecosystems and the structure and dynamics of biological communities	Mace et al. (2012)	Incomplete: ecological processes should also include interactions between organism and their abiotic environment, since these have an important impact on organism-level attributes (such as survival)
Ecosystem processes	***Transfer of energy, material, or organisms among pools in an ecosystem***	***Lovett*** et al. ***(2006)***	***Clearly excludes organism-level processes; does not refer to stocks of materials***
	Complex physical and biological cycles and interactions that underlie what we observe as the natural world	Brown et al. (2007)	Vague; fails to establish the distinction between ecological and ecosystem processes
	Changes in the stocks and/or flows of materials in an ecosystem, resulting from interactions among organisms and with their physical–chemical environment	Mace et al. (2012)	Fails to establish the distinction between ecological and ecosystem processes
Ecosystem functions	Refer variously to the habitat, biological or system properties or processes of ecosystems	Costanza et al. (1997)	Vague: fails to establish the distinction between ecosystem functions and ecosystem processes
	Ecosystem processes and ecosystem stability	Bengtsson (1998)	Fails to establish the distinction between ecosystem functions and ecosystem processes
	Stocks of energy and materials (e.g. biomass), fluxes of energy or material processing (e.g. productivity, decomposition), and the stability of rates or stocks over time	Pacala and Kinzig (2002)	Subsumes ecosystem structure ('stock') under the concept of 'function'; fails to establish the distinction between ecosystem functions and ecosystem processes
	The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly	De Groot et al. (2002)	Fails to establish the distinction between ecosystem functions and ecosystem services
	Attributes related to the performance of an ecosystem that is the consequence of one or of multiple ecosystem processes	***Lovett*** et al. ***(2006)***	***Explicitly relates the concept of ecosystem processes to ecosystem functions***
	The subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services	Kumar (2010)	Conflates structural and compositional attributes of biodiversity ('stocks') with functional aspects ('fluxes')
	The ecological processes that control the fluxes of energy, nutrients and organic matter through an environment	Cardinale et al. (2012)	Fails to establish the distinction between ecosystem processes, ecological processes and ecosystem functions
	The energy, matter, and information fluxes linking ecosystem compartments	Meyer et al. (2015)	Fails to establish the distinction between ecosystem processes and ecosystem functions
	The biological underpinning of ecosystem services	Oliver et al. (2015)	Vague; does not clearly separate function from structure
Ecosystem services	The conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life	Daily (1997)	Vague; the relationship between ecosystem functions and services is unclear
	The benefits human populations derive, directly or indirectly, from ecosystem functions	***Costanza*** et al. ***(1997)***	***Provides a clear link to ecosystem functions***
	The benefits people derive from ecosystems	Millennium Ecosystem Assessment (2005)	Vague; the relationship between ecosystem functions and services is unclear
	Ecosystem services are the aspects of the ecosystems utilized (actively or passively) to produce human well-being	Fisher et al. 2009	Vague; the relationship between ecosystem functions and services is unclear
	Direct and indirect contributions of ecosystems to human well-being	TEEB (2010)	Vague; the relationship between ecosystem functions and services is unclear

(*Continued*)

Table 1. Continued.

Concept	Definition	Reference	Benefit/Drawback
	Outputs of ecosystem processes that provide benefits to humans (e.g. crop and timber production)	Oliver et al. (2015)	The relationship between ecosystem functions and services is unclear
	Those functions and products of an ecosystem that directly or indirectly benefit humans. Often ecosystem functions are considered a service when they can be attributed an economical value	Meyer et al. (2015)	Definition not as well-known as that of Costanza et al. 1997, but does not contradict it

The definitions adopted for our framework appear in italic bold.

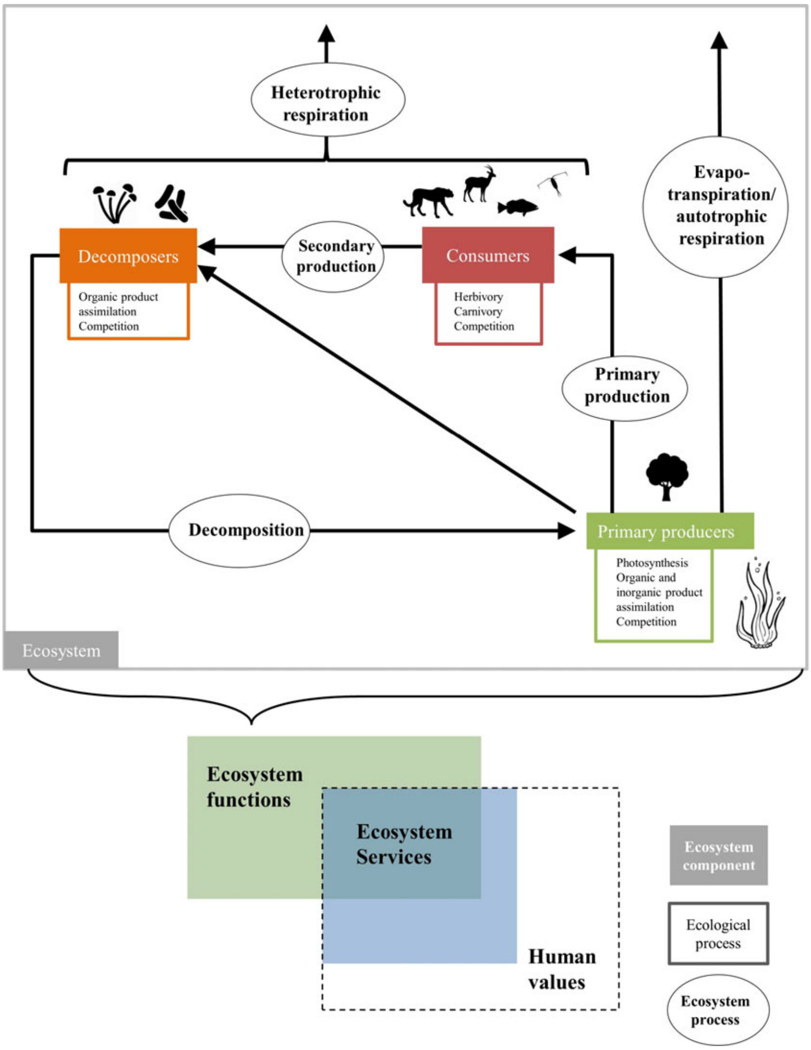

Figure 1. Simplified representation of the links between ecological processes, ecosystem processes, ecosystem functions and ecosystem services. Decomposers, consumers and primary producers represent the main pools of a given ecosystem. Ecological processes mostly occur within each pool; examples of ecological processes are listed under each pool. Ecosystem processes capture the transfer of energy, material, or organisms among pools; examples of ecosystem processes appear in circles. Ecosystem functions represent attributes related to the performance of an ecosystem; they are the consequence of one or of multiple ecosystem processes. Finally, ecosystem services are those elements of ecosystem functions that benefit people.

Introducing a typology of ecosystem functions

Although the concept of ecosystem function is not new (Odum 1969), only recently have attempts been made to identify and classify ecosystem functions. The first attempt to comprehensively identify and classify ecosystem functions can be traced to de Groot and colleagues in 2002; their list has been used by many as a starting point for establishing monitoring protocols for ecosystem functions and ecosystem services (see e.g. Wallace 2007; Petter et al. 2012). The main issue with this original classification is the confusion between ecosystem functions and ecosystem services, which led de Groot and colleagues to include 'information functions', such as aesthetic information, recreation, cultural and artistic information, spiritual and historic information, as well as science and education, in their typology of ecosystem functions. De Groot et al.'s typology was later refined by others, including Petter et al. (2012), who identified 19 terrestrial ecosystem functions. This typology is particularly relevant to developing an implementable global monitoring framework for ecosystem functions, as it was used by the authors to map these individual functions for the South East Queensland region in Australia. However, it does mention the existence of a cultural function, which reflects the interests of the authors in using ecosystem function mapping as a way to derive information about spatial variation in ecosystem services for this region. Because this cultural function was clearly based on anthropocentric values, it does not fit our definition of ecosystem functions. In the marine realm, typologies of ecosystem functions are also rarely discussed. One exception is the work by Boero and Bonsdorff (2007) who distinguished three broad groups of functions based on basic cycles of matter and energy, namely (i) extraspecific cycles (biogeochemical cycles), (ii) intraspecific cycles (life cycles and histories), and (iii) interspecific cycles (food webs). However, their definition of ecosystem functions does not distinguish between organism- and ecosystem-level processes.

We here propose a new ecosystem function typology, which broadens the definitions of the candidate functions identified by Petter and colleagues in 2012, making them relevant to all ecological realms. This new typology lines up with the widely accepted Millennium Ecosystem Assessment typology for ecosystem services (MEA 2005), thus allowing clear links between the two frameworks. Because we vetted our list against Lovett et al. (2006)'s definition of ecosystem functions (Table 2), our proposed typology excludes cultural functions (as they are ecosystem services), and thus only distinguishes 18 ecosystem functions, which are all shaped by different ecological and ecosystem processes (Table 2). These 18 functions can be broadly classified into regulating functions (which control the magnitude of ecosystem processes, such as climate regulation and biological control), provisioning functions (which provide all organisms with the resources necessary for their survival and reproduction, such as water supply and provision of food), and supporting functions (which underpin the continued functioning of the ecosystem, such as the formation and retention of soil and sediment, and pollination/larval and seed dispersal). A definition of each of these functions, as well as examples of ecological and ecosystem processes that underpin the delivery of these functions can be found in Table 2 and Figure 2.

Satellite Remote Sensing of Ecosystem Functions

Opportunities

A wealth of methods is currently available to monitor various ecosystem functions that rely on the collection of field data (Meyer et al. 2015); however, on their own, none can realistically be scaled up to reach global coverage on a regular (daily, weekly, monthly) basis. For example, Steenweg et al. (2017) suggest a framework for global monitoring of biodiversity with large-scale camera networks but major limitations include inconsistent metadata, data access, intellectual property and privacy considerations. Satellite remote sensing measurements, on the other hand, are widely accessible, and offer a relatively inexpensive and verifiable means of deriving complete spatial coverage of environmental information for large areas at different spatial and temporal resolutions in a consistent manner (Pettorelli et al. 2014), holding great potential for tracking changes in ecosystem functions (Cabello et al. 2012; Nagendra et al. 2013; Pettorelli 2013).

An agreed methodology for satellite remote sensing of ecosystem functions could offer many opportunities to advance ecology and conservation, allowing, for example, to test emerging theories and unveil the processes shaping the impacts of anthropogenic threats on biodiversity more rapidly. For example, selective defaunation of tropical forests from bushmeat hunting can lead to loss of aboveground biomass, reduced forest carbon sequestration and impacts on climate regulation (Jansen et al. 2010). Traditionally, these processes would be measured in the field (Camargo-Sanabria et al. 2015) at great expense (e.g. using plot-based tree censuses) but at scales that might not suffice to distinguish between changes in aboveground biomass and carbon storage (Harrison et al. 2013). In situations like this, the ability to track changes in these functions across broad regions using satellite data could enable more rapid detection of potential secondary

Table 2. Typology of ecosystem functions, with examples of ecological and ecosystem processes underpinning the delivery of a given function.

			Examples of underpinning	
Type	Function	Description	Ecological processes	Ecosystem processes
Regulating	Gas regulation	Role of ecosystems in bio-geochemical cycles (such as CO_2/O_2 balance, ozone layer)	Cellular respiration Coral reef calcification	Heterotrophic respiration
	Climate regulation	Influence of ecosystems on climate	Photosynthesis	Evapotranspiration Decomposition Primary production
	Disturbance regulation	Influence of ecosystem attributes on environmental disturbances	Vegetation modulating surface resistance and infiltration Wind and wave energy absorption by e.g. seagrasses and mangrove vegetation	Primary production Decomposition
	Water regulation	Role of ecosystems in regulating runoff and river discharge	Vegetation modulating surface resistance and infiltration	Primary production Evapotranspiration
	Nutrient regulation	Role of ecosystems in the transport, storage and recycling of nutrients	Herbivory Predation Mineralization Nitrogen fixation Marine bioturbation Soil turnover (fossorial fauna)	Decomposition Hypertrophication
	Biological control	The interactions within biotic communities that restrain the impact of outbreaks/blooms of specific populations of species on the functioning of the ecosystem, e.g. by controlling population of potential pests and disease vectors	Herbivory Competition Predation Parasitism	Secondary production
Provisioning	Provision of food	Biomass that sustains living organisms. Material that can be converted to provide energy and nutrition.	Detrivory Mineralization	Primary production Secondary production
	Provision of raw materials	Biomass that is used by organisms for any purpose other than food	Tree death Coral death	Primary production
	Water supply	The role of ecosystems in providing water	Vegetation facilitating infiltration	Primary production Evapotranspiration
	Provision of shade/shelter	Relates to vegetation/structures that ameliorates extremes in weather and climate at a local landscape/seascape scale	Tree death Coral reef calcification	Primary production
	Pharmacological resources production	Natural materials that are or can be used by organisms to maintain, restore or improve health	Herbivory Predation Competition	Primary production
	Supporting habitats	Preservation of natural and semi-natural ecosystems as suitable living space for wild biotic communities and individual species. This function also includes the provision of suitable breeding, reproduction, nursery, refugia and corridors (connectivity).	Herbivory Predation Competition Tree death Coral death	Primary production Secondary production Decomposition

(*Continued*)

Table 2. Continued.

Type	Function	Description	Examples of underpinning	
			Ecological processes	Ecosystem processes
	Production of genetic resources	Self-maintaining diversity of organisms developed over evolutionary time (capable of continuing to change)	Herbivory Predation Competition	Primary production Secondary production
Supporting	Soil/sediment retention	Role of vegetation root matrix and soil biota in soil/sediment retention	Root zone competition Erosion	Primary production
	Waste treatment and assimilation	Role of biota in transport, storage and recycling of organic and inorganic wastes (defined here as by-products generated by a given set of organisms)	Organic and inorganic product assimilation Filter feeding	Decomposition Hypertrophication
	Pollination/dispersal (of seed and larvae)	Role of biota in movement of floral gametes and seeds, or aquatic/marine spores, eggs and larvae	Predation Herbivory Nectarivory	Primary production
	Barrier effect of vegetation/coral structures	Vegetation/structures impedes the movement of airborne and waterborne substances such as particulate matter, dust and aerosols (including agricultural chemicals and industrial and transport emissions), enhances air mixing and mitigates noise	Coral reef calcification	Primary production
	Soil/Sediment formation	Facilitation of soil/sediment formation processes	Biological weathering of rocks Sediment trapping	Primary production Decomposition

effects of defaunation on tropical forest functions, allowing for more targeted field data collection and faster development and implementation of effective management actions (Osuri et al. 2016; Peres et al. 2016).

As with most conceptual frameworks that inform our understanding of the natural world (Stephens et al. 2015), ecosystem functions ultimately relate to entities that can be hard to measure directly and are the result of multiple ecosystem processes (Table 2; Fig. 2). Hence, the monitoring a given ecosystem function will mostly depend on the tracking of many relevant indicators. Table 3 provides a non-exhaustive list of open-access satellite remote sensing products that could contribute to the dynamic, global monitoring of ecosystem functions: as one can see, a range of ecosystem function indicators is already well supported by existing products (Table 3). In addition, upcoming satellite missions will increase the level of detail and accuracy with which we can map ecosystem functions, as well as opening new monitoring opportunities (Table 4). The Sentinel missions in particular could become a game changer for comprehensive global ecosystem function monitoring, since they (i) carry a range of sensors relevant to land, ocean and atmospheric monitoring; (ii) provide the only global, open-access radar imagery (Sentinel 1); (iii) allow gathering data at both high temporal (5 days) and spatial resolutions (5–10 m). Future spaceborne hyperspectral sensor missions (such as the Environmental Mapping and Analysis Program (EnMAP), the Hyperspectral Infrared Imager (HyspIRI), and the Hyperspectral Precursor of the Application Mission (PRISMA – Italian Space Agency) could moreover provide unprecedented opportunities to characterize surface chemistry and structure in great detail (Chambers et al. 2007). Data collected by these missions could indeed expand ecosystem monitoring capacity significantly, especially with regard to carbon and water vapour flux modelling (Fuentes et al. 2006), chemical composition of foliage (Schlerf et al. 2010), early detection of defoliators (Fassnacht et al. 2014), accurate mapping of burned areas (Veraverbeke et al. 2014), permafrost monitoring (Buchhorn et al. 2013) and measurements of ecosystem methane emissions (Thompson et al. 2015), complementing the monitoring capacity of existing sensors (Guanter et al. 2015). Monitoring of biomass (Hyde et al. 2007; Nelson et al. 2007) and canopy structure (Vierling et al. 2008; Lefsky 2010; Enßle et al. 2014) are also likely to be facilitated by the availability of global LiDAR data from spaceborne missions (e.g. ICESat-2 and GEDI; Patterson and Healey 2015; Brown et al. 2016). Beyond new satellite missions, advances in data processing are also likely to expand ecosystem function monitoring capacities. For instance, image fusion techniques allow combining imagery with high spatial, low temporal

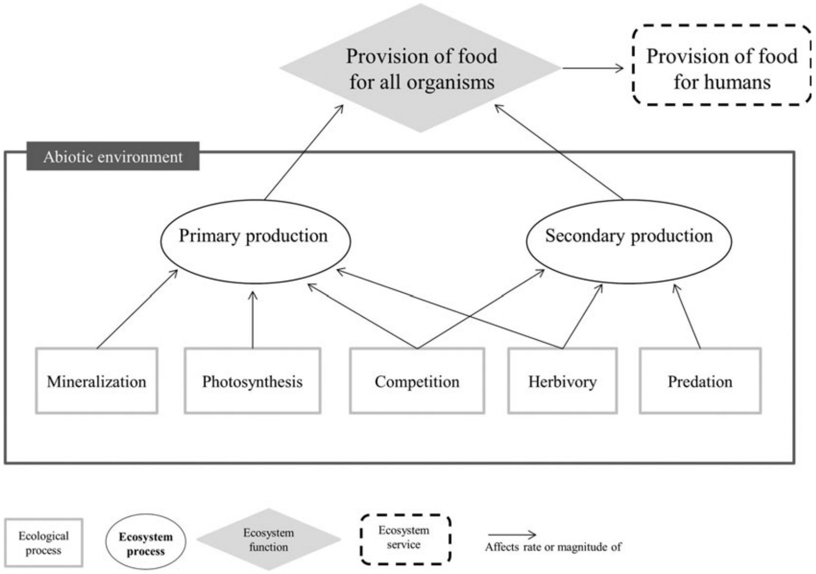

Figure 2. Example of ecological and ecosystem processes underpinning the food provision function. Different 'types of food' (e.g., vegetal, animal) can be produced by ecosystems, and each type can be tracked using indicators related to the two major ecosystem processes underpinning the production of these food (namely primary and secondary productivity). Each ecosystem process is itself shaped by multiple ecological processes, such as photosynthesis, competition, herbivory, predation and mineralization.

resolution (e.g. Landsat) and imagery with low spatial, high temporal resolution (e.g. MODIS) into time series with high spatial, high temporal resolution (Gao et al. 2006; Schmidt et al. 2015), which could support a better characterization of vegetation phenology.

Limitations

Monitoring ecosystem functions, using satellite data or ground-based information, first necessitates agreement on what ecosystem functions are, but also on what ecosystems are and where their boundaries lie (Likens 1992). Such difficulties are not limited to ecosystems, with similar discussions arising when considering populations or species (see e.g. Mallet 1995; Berryman 2002). The Red List of Ecosystems offers a comprehensive framework for defining and monitoring ecosystems (Bland et al. 2016), and as such could be used as a reference point for agreeing on where boundaries should be set. Doing so would allow complementarity and effectiveness in efforts to monitor, and report on, the state of ecosystems globally.

As demonstrated in Table 3, monitoring ecosystem function then involves making a number of choices in terms of which indicators and which proxies to consider; these choices may all have implications for the reliability of the inferred trends. Satellite remote sensing is moreover associated with intrinsic limitations, which have been discussed at length (see e.g. Pettorelli 2013; Pettorelli et al. 2014, 2016); one can thus expect data product characteristics (spatial, temporal, spectral resolutions) to influence mapping accuracy and monitoring opportunities for certain ecosystem functions in certain environments. Integrated use of multiple remote sensing sources and increased remote sensing capacity can help overcome many of these known challenges, as long as data and product requirements are clearly identified: the prioritization of new satellite missions associated with freely accessible data for scientific use might indeed be facilitated by the formulation of clear, consensual demands from ecosystem researchers (Paganini et al. 2016).

Discussions around the monitoring of ecosystem functions will need to involve clarity on which processes are being monitored for each considered ecosystem function; what the reliability and sensitivity of each considered proxy are; what aggregation method is being used (if any) to integrate the collated information relating to the ecosystem processes that shape a given ecosystem function; and how the choices made affect decision-making robustness in a given context (Stephens et al. 2015). Remote sensing proxies will often need to be combined with field measurements to accurately represent the desired ecosystem function (e.g. Tong et al. 2004). Indeed, joint analysis of satellite data with *in situ* measurements, or process measurements in the lab, may be essential steps to the refinement and increased capacity and utility, of satellite-based indicators for ecosystem function monitoring (Racault et al. 2014). This is likely to be a non-trivial task, particularly in highly dynamic

Table 3. Non-exhaustive list of freely available, global satellite remote sensing data products that open opportunities for the dynamic monitoring of ecosystem functions.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product	Examples
Gas regulation	Gas concentrations	Total ozone burden	Terra/Aqua (MODIS)	MODIS Atmospheric Profile product	Spichtinger et al. (2001) used GOME-derived nitrogen oxide concentration to map emissions from boreal forest fires.
			Nimbus-7/Meteor-3/Earth Probe	Total Ozone Mapping Spectrometer (TOMS) (1978-2006)	
			Sentinel-5P (TROPOMI)	O_3 tropospheric profile	
		Total methane burden	Aqua (AIRS)	Methane product	Ribeiro et al. (2016) used the Aqua (AIRS) Methane product to link methane concentrations over the Amazon to wetness and biomass burning.
	Emissions of gases by ecosystems	Air-sea CO_2 flux	Multiple, including POES (AVHRR), Terra/Aqua (MODIS), TRMM (CERES)	NOAA AOML Surface CO_2 Flux maps (1982–2009)	
Climate regulation	Temperature regulation	Land and sea surface temperature	Terra/Aqua (MODIS)	MODIS Land Surface Temperature and Emissivity	Jin and Dickinson (2010) used Terra (MODIS) data to derive land skin temperature and investigate its relationship with local surface albedo and vegetation, among other parameters.
			Terra/Aqua (MODIS)	MODIS Sea Surface Temperature	
			POES (AVHRR)	NOAA Coral Reef Watch Sea Surface Temperature	
			Sentinel 3 (SLSTR)	Ocean/Sea Surface Temperature Land Surface Temperature	
	Precipitation regulation	Rainfall	TRMM (PR, TMI, VIRS, CERES)	TRMM precipitation estimates (1998–2015)	
			TRMM (PR, TMI, VIRS, CERES)	CHIRPS	
			TRMM (PR, TMI, VIRS, CERES)	GPCP	
		Evapotranspiration	Terra/Aqua (MODIS)	MODIS evapotranspiration	
			Landsat (TM, ETM+, OLI/TIRS)	Landsat evapotranspiration	
		Cloud cover	Terra/Aqua (MODIS)	MODIS Cloud Cover	
			CloudSat (CALIPSO)	CALIPSO Cloud Cover (2006-2011)	
			Sentinel-5P (TROPOMI)	Fractional cloud cover	
	Ocean carbon cycle regulation	Coral reef calcification	OCEANSAT (OCM)	Ocean Colour Monitor (OCM)	
			Merged MERIS, Aqua-MODIS, SeaWiFS and VIIRS data	ESA Ocean Colour CCI product	
Disturbance regulation	Fire occurrence	Fire hotspots	Terra/Aqua (MODIS)	MODIS FIRMS	Hantson et al. (2015) used the MODIS Burned Area product to investigate what drives the distribution of fire extent worldwide.
	Extent of fire damages	Extent of burned area	Terra/Aqua (MODIS)	MODIS Burned Area Product	
			SPOT (HRV, HRVIR, HRG)	SPOT VGT Burned Area	
	Flood occurrence	Standing water	Terra/Aqua (MODIS)	NRT Global Flood Mapping	
			TRMM (CERES)	Global Flood Monitoring System	
			DMSP (SSM/I), ERS-1, POES (AVHRR)	Global Inundation Extent from Multi-Satellites (1993–2007)	NOAA CRW products were used to monitor the Great Barrier Reef during the 2002 bleaching event (Liu et al. 2003).
	Drought occurrence	Standardized precipitation index (SPI)	TRMM (PR, TMI, VIRS, CERES)	Satellite-Based Global Drought Climate Data Record	
		Water-content in standing vegetation	Nimbus-7 (SMMR), DMSP (SSM/I), TRMM (TMI)	Vegetation Optical Depth from VUA-NASA Land Parameter Retrieval Model	Harvey et al. (2015) used MERIS data to monitor chlorophyll- α concentration in coastal waters.

(*Continued*)

Table 3. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product	Examples
	Defoliator outbreaks	Changes in maximum NDVI	POES (AVHRR) Terra/Aqua (MODIS)	GIMMS NDVI (1981–2011) MODIS NDVI	
	Coral bleaching	Sea surface temperature	POES (AVHRR)	NOAA Coral Reef Watch products	
		Hotspots of sea surface temperature	POES (AVHRR)	NOAA Coral Reef Watch products	
		Degree Heating Weeks	POES (AVHRR)	NOAA Coral Reef Watch products	
		Bleaching Alert Areas	POES (AVHRR)	NOAA Coral Reef Watch products	
	Eutrophication of water bodies	Ocean Colour	ENVISAT (MERIS) Terra/Aqua (MODIS) Orb-View-2 (SeaWiFS) Sentinel 3 (OLCI)	Ocean colour (total suspended matter) data from MERIS, MODIS and SeaWiFS Color dissolved organic matter/ yellow substance (CDOM)	
Water regulation	Inland water dynamic	Change in water stage	Sentinel 3 (SRAL)	Sentinel 3 altimetry (lakes level)	Spera et al. (2016) used MODIS evaporation data to track the effect of land cover change on regional water dynamics in the Cerrado biome.
		Water body distribution	Terra/Aqua (MODIS) Landsat (TM, ETM+)	MODIS Water Mask Global Surface Water (1984–2015)	
Soil/Sediment retention	Sediment plumes	Turbidity	ENVISAT (MERIS) Terra/Aqua (MODIS) Orb-View-2 (SeaWiFS)	Ocean colour (total suspended matter) data from MERIS, MODIS and SeaWiFS	Valente and da Silva (2009) used an MODIS Ocean Colour product to monitor a turbid plume in an estuary.
		Suspended sediment	Sentinel 3 (OLCI)	Suspended sediment concentration	
Nutrient regulation	Nutrient availability	Algal bloom	Many, including ENVISAT (MERIS), Terra/Aqua (MODIS), Orb-View-2 (SeaWiFS), VIIRS	Ocean colour data from GlobCover, ESA-CCI	Huang et al. (2014) used Landsat and MODIS data to characterize eutrophication in response to land use change in a lake's catchment.
		Chlorophyll-α concentration	Many, including MODIS, MERIS, VIIRS, GOCI, SeaWiFS, CZCS	Chlorophyll- α product from NASA Ocean Color project	
Pollination	Vegetation phenology	Temporal dynamics of seasonal changes in vegetation indices	Terra/Aqua (MODIS) Metop (AVHRR) Terra/Aqua (MODIS)	MODIS NDVI AVHRR NDVI3 g (1981–2011) MODIS EVI	Schulp and Alkemade (2011) mapped pollination efficiency using the GLOBCOVER land cover product.
	Primary productivity	SRS-based primary productivity estimates	Terra/Aqua (MODIS)	MODIS Gross Primary Production or Net Primary Production	
Biological control	Defoliator control	Changes in maximum NDVI	Terra/Aqua (MODIS)	MODIS NDVI	Spruce et al. (2011) used MODIS NDVI time series to map defoliation by European gypsy moth *Lymantria dispar* in North America.

(*Continued*)

Table 3. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product	Examples
Barrier effect of vegetation	Vegetation barriers	Forest cover	Landsat (TM, ETM+, OLI)	Landsat Global Forest Cover Change (2000–2012)	Carniello et al. (2014) used Landsat-derived maps of benthic vegetation to account for their barrier effect in a model of coastal sediment dynamics.
			Terra/Aqua (MODIS)	MODIS Land Cover Type	
		Tree cover	Terra/Aqua (MODIS)	MODIS Vegetation Continuous Fields (2000–2013)	
			Landsat (TM, ETM+, OLI)	Landsat Tree Cover Continuous Fields (2000 & 2005)	
	Air quality	Aerosol particles	Terra (MODIS)	Aerosol Optical Thickness	
			CALIPSO (CALIOP/IIR/WFC)	CALIPSO All-Sky Aerosol Extinction product	
			CALIPSO (CALIOP/IIR/WFC)	CALIPOSO Aerosol Profiles and Layer products	
		Nitrogen dioxide	Metop (GOME)	GOME or SCIAMACY Nitrogen Dioxide	
			ENVISAT (Sciamacy)		
		Sulfur dioxide	Aura (OMI)	OMI/Aura sulfur dioxide abundance	
	Wind speed	SRS-based wind speed estimates	QuikSCAT (SeaWinds)	QuikSCAT wind speed	
Supporting habitats	Habitat extent	Land cover	ENVISAT (MERIS)	ESA global land cover maps for 2000, 2005 and 2010 (MERIS and SPOT)	Harwood et al. (2016) improved habitat condition assessments across Australia using two land cover products (based on AVHRR and MODIS).
			SPOT (HRV, HRVIR, HRG)		
			Terra/Aqua (MODIS)	MODIS Land Cover Type	
		Forest cover	Landsat (TM, ETM+, OLI)	Landsat Global Forest Cover Change (2000–2014)	
			Terra/Aqua (MODIS)	MODIS Land Cover Type	
		Tree cover	Terra/Aqua (MODIS)	MODIS Vegetation Continuous Fields (2000–2013)	
			Landsat (TM, ETM+, OLI)	Landsat Tree Cover Continuous Fields (2000 & 2005)	
		Water body distribution	Terra/Aqua (MODIS)	MODIS Water Mask	
		Inland water dynamic	Landsat (TM, ETM+)	Global Surface Water (1984–2015)	
		Sea ice	Nimbus-7 (SMMR)	Sea Ice Concentration (from Nimbus-7 and DMSP)	
			DMSP (SSM/I, SSMIS)		
			GRACE (KBR)	GRACE Monthly surface mass changes	
			Cryosat (SIRAL)	Cryosat ice thickness	
		Glaciers	Terra (ASTER)	GLIMS	
	Habitat quality	Salinity	SMOS (MIRAS)	SMOS salinity	
			SAC-D (Aquarius)	Aquarius sea surface salinity (2011–2015)	

(*Continued*)

Table 3. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product	Examples
		Albedo	Terra/Aqua (MODIS)	MODIS Surface Albedo product	
		Soil moisture	SMAP (SMAP Radiometer)	Soil moisture Product	
			Multiple, including ERS-1/2, Metop, DMSP(SSM/I), TRMM(TMI)	ESA CCI Soil Moisture	
		SRS-based primary productivity estimates	Terra/Aqua (MODIS)	MODIS Chlorophyll α	
			Terra/Aqua (MODIS)	MODIS Gross Primary Production/Net Primary Production	
		Sea surface temperature	Terra/Aqua (MODIS)	MODIS Sea Surface temperature	
Sediment formation	Deposition	Surface particle size distribution	Terra (ASTER)	ASTER SWIR and TIR mineral products	Villar et al. (2013) used MODIS surface reflectance data to predict sedimentation rates in a river
Food	Production of vegetal biomass	SRS-based primary productivity estimates	Terra/Aqua (MODIS)	MODIS Gross Primary Production/Net Primary Production	Malmstrom et al. (2009) used Landsat-derived biomass estimates to investigate effects of different grassland restoration treatments on forage availability
			Many, including ENVISAT (MERIS), Terra/Aqua (MODIS), Orb-View-2 (SeaWiFS), VIIRS	Ocean colour (total suspended matter)	
		Vegetation indices	Terra/Aqua (MODIS)	MODIS FAPAR	
			Terra/Aqua (MODIS)	MODIS LAI	
			Terra/Aqua (MODIS)	MODIS Chlorophyll α	
		Land cover	Terra/Aqua (MODIS)	MODIS Land Cover	
	Production of fish stocks	Chloropyll-a concentration	Many, including MODIS, MERIS, VIIRS, GOCI, SeaWiFS, CZCS	Chlorophyll-α product from NASA Ocean Color project	
		Sea surface temperature	Terra/Aqua (MODIS)	MODIS Sea Surface temperature	
Raw materials	Wood and NTFP	Tree cover	Terra/Aqua (MODIS)	MODIS Vegetation Continuous Fields (2000-2013)	Cudahy et al. (2016) used ASTER to map mineral composition of vegetation-free surfaces across Australia
			Landsat (TM, ETM+, OLI)	Landsat Tree Cover Continuous Fields (2000 & 2005)	
Water supply	Water availability	Evapotranspiration	Terra/Aqua (MODIS)	MODIS evapotranspiration	Senay et al. (2013) used ASTER surface reflectance to map water holes in semi-arid rangelands and then used satellite-derived precipitation and digital elevation to monitor their water levels Semmens et al. (2016) used Landsat 8, MODIS and GOES to monitor daily evapotranspiration in vineyards
			Landsat (TM, ETM+, OLI/TIRS)	Landsat evapotranspiration	
			Many, including Terra/Aqua (MODIS), TRMM (CERES), DMSP (SSM/I)	Evapotranspiration data from the Global Land Evaporation Amsterdam Model (GLEAM)	
		Snow cover	Terra/Aqua (MODIS)	MODIS Snow Cover	

(*Continued*)

Table 3. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product	Examples
					Huang et al. (2016) produced a MODIS snow cover product to estimate spatio-temporal changes in snow cover across China
Provision of shade and shelter	Extent to which vegetation shades the ground	Tree cover	Terra/Aqua (MODIS)	MODIS Vegetation Continuous Fields (2000-2013)	Guzy et al. (2015) use LiDAR to estimate the effect of riparian vegetation cover on urban stream shade and stream restoration potential
			Landsat (TM, ETM+, OLI)	Landsat Tree Cover Continuous Fields (2000 & 2005)	
		Plant canopy	Terra/Aqua (MODIS)	MODIS Leaf Area Index	
Pharmacological resources	Availability of plants	SRS-based primary productivity estimates	Terra/Aqua (MODIS)	MODIS Gross Primary Production/Net Primary Production	No example found for this particular function

Most are currently routinely produced; discontinued products (based on existing sensors) were included too, when they could conceivably contribute to elaborating a monitoring scheme for a given function (since routine production could be resumed). In such cases, the time period for which they are available was stated.

AIRS, Atmospheric Infrared Sounder; AOML, Atlantic Oceanographic and Meteorological Laboratory, ASTER SWIR and TIR, Advanced Spaceborne Thermal Emission and Reflection Radiometer Short Wave Infrared and Thermal Infrared; AVHRR, Advanced Very High Resolution Radiometer; AVISO, Archiving, Validation and Interpretation of Satellite Oceanographic data; CALIOP, Cloud-Aerosol Lidar with Orthogonal Polarization; CALIPSO, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; CCI,Climate Change Initiative; CERES, Clouds and the Earth's Radiant Energy System; CHIRPS, Climate Hazards Group InfraRed Precipitation with Station data; CZCS, Coastal Zone Color Scanner; DMSP, Defense Meteorological Satellite Platform; ENVISAT, Environmental Satellite; ERS, European Remote Sensing Satellites; ESA, European Space Agency; ETM+, Enhanced Thematic Mapper Plus; EVI,Enhanced vegetation index; FAPAR, Fraction of absorbed Photosynthetic Active Radiation; FIRMS, Fire Information for Resource Management System; GIMMS, Global Inventory Modeling and Mapping Studies; GLIMS, Global Land Ice Measurements from Space; GOCI, Geostationary Ocean Color Imager; GOME, Global Ozone Monitoring Experiment; GPCP, Global Precipitation Climatology Project; GRACE, Gravity Recovery And Climate Experiment; GSFC, Goddard Space Flight Center; HRG, High Resolution Geometric; HRV, High Resolution Visible; HRVIR, High Resolution Visible and Infrared; IIR, Infrared Imaging Radiometer; KBR, K-Band Ranging System; LAI, Leaf Area Index; MERIS, Medium Resolution Imaging Spectrometer; MIRAS, Microwave Imaging Radiometer with Aperture Synthesis; MODIS, Moderate Resolution Imaging Spectroradiometer; NASA, National Aeronautics and Space Administration; NDVI, Normalized Difference Vegetation Index; NFTP, Non-Timber Forest Product; NOAA, National Oceanic and Atmospheric Administration; NRT, Near Real Time; OLCI, Ocean and Land Colour Instrument; OLI, Operational Land Imager; POES, Polar Operational Environmental Satellites; PR, Precipitation Radar; SAC-D, Satelite de Aplicaciones Cientificas; SCIAMACY, Scanning Imaging Absorption Spectrometer for Atmospheric Cartography; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; SIRAL, Synthetic Aperture Interferometric Radar Altimeter; SMAP, Soil Moisture Active Passive; SMMR, Scanning Multichannel Microwave Radiometer; SMOS, Soil Moisture and Ocean Salinity; SPOT, Satellite Pour l'Observation de la Terre; SSM/I, Special Sensor Microwave Imager; SSMIS, Special Sensor Microwave Imager Sounder; TIRS, Thermal Infrared Sensor; TM, Thematic Mapper; TMI,TRMM Microwave Imager; TROPOMI, Tropospheric Monitoring Instrument; OMI, Ozone Monitoring Instrument; TRMM, Tropical Rainfall Measuring Mission; VGT, Vegetation; VIIRS, Visible Infrared Imaging Radiometer Suite; VIRS, Visible and Infrared Scanner; VUA, VU University Amsterdam; WFC, Wide Field Camera.

Table 4. Non-exhaustive list of potential future satellite remote sensing data products that could expand ecosystem function monitoring capacity.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product
Gas regulation	Emissions of gases by ecosystems	Emissions from fire	HyspIRI (VSWIR/TIR)	HyspIRI fire emissions
			HyspIRI (VSWIR/TIR)	HyspIRI volcano eruptions and emissions
Climate regulation	Precipitation regulation	Evapotranspiration	HyspIRI (VSWIR/TIR)	HyspIRI evapotranspiration
	Ocean carbon cycle regulation	Oceanic particulate organic carbon stock	Aqua (MODIS)	Potential future product
		Oceanic biological carbon stock	ESA-CCI	Potential future product
		Ocean acidification	NOAA	Potential future product
Disturbance regulation	Fire occurrence	Fire hotspots	HyspIRI (VSWIR/TIR)	HyspIRI fuel status
		Fire temperature	Sentinel 3 (SLSTR)	Sentinel 3 Fire temperature
	Extent of fire damages	Extent of burned area	Proba V (Vegetation)	Proba V Burned Area
			HyspIRI (VSWIR/TIR)	HyspIRI biomass burning
			Sentinel 2 (MSI), Sentinel 3 (OLCI, SLSTR)	Sentinel 2 and 3 Burnt Area
	Flood occurrence	Standing water	Terra/Aqua (MODIS)	MODIS daily surface water extent (using the Open Water Likelihood algorithm)
			Sentinel 1 (SAR)	Sentinel 1 Floods (Standing water)
	Defoliator outbreaks	Changes in maximum NDVI	Proba V (Vegetation)	Proba V NDVI
	Coral bleaching	Status of coral reefs	HyspIRI (VSWIR/TIR)	HyspIRI global composition and status of coral reefs and coastal habitats
	Eutrophication of water bodies	Cholorophyll-α concentration	Sentinel 3 (OLCI)	Ocean chlorophyll
Water regulation	Inland water dynamic	Change in surface water extent	Terra/Aqua (MODIS)	MODIS daily surface water extent (using the Open Water Likelihood algorithm)
		Change in water stage	TRMM (PR, TMI, VIRS, CERES)	Water stage (Puri et al. 2011)
Nutrient regulation	Nutrient availability	Chlorophyll concentration	Sentinel 3 (OLCI)	Ocean chlorophyll
Waste treatment and assimilation	Presence of waste products in the soil	Soil nitrogen/presence of heavy metals	Landsat (TM)	Soil nitrogen/heavy metals derived from surface reflectance (Peng et al. 2016)
Pollination	Vegetation phenology	Timing and magnitude of seasonal changes in Normalized Difference Vegetation Index (NDVI)	Proba V (Vegetation)	Proba V NDVI
			Landsat (TM, ETM+, OLI)	NDVI derived from Landsat surface reflectance product alone or derived from MODIS-Landsat fused time series (Hilker et al. 2009; Walker et al. 2012)
			Terra/Aqua (MODIS)	
			Sentinel 2 (MSI)	NDVI derived from Sentinel 2
		Timing and magnitude of other vegetation indices	Terra/Aqua (MODIS)	MODIS Visible atmospherically resistant index (VARI)
			EnMAP (VNIR/SWIR)	EnMAP terrestrial phenology
			FLEX (FLORIS)	FLEX photosynthetic activity
	Production of biomass	SRS-based estimates of primary productivity	FLEX (FLORIS)	FLEX primary productivity
			Proba V (Vegetation)	Proba V vegetation productivity index
			Proba V (Vegetation)	SPOT VGT or Proba V Dry Matter Productivity product
			SPOT (HRV, HRVIR, HRG)	

(*Continued*)

Table 4. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product
Biological control	Defoliator control	Changes in maximum NDVI	Proba V (Vegetation)	Proba V NDVI
			Landsat (TM, ETM+, OLI) Terra/Aqua (MODIS)	NDVI derived from Landsat surface reflectance product alone or derived from MODIS-Landsat fused time series (Hilker et al. 2009; Walker et al. 2012)
			Sentinel 2 (MSI)	NDVI derived from Sentinel 2
		Defoliator presence	EnMAP (VNIR/SWIR) HyspIRI (VSWIR/TIR)	EnMAP or HyspIRI Infestation Identification
	Harmful algal bloom control	Harmful algal bloom extent	ENVISAT (MERIS) Terra/Aqua (MODIS) Orb-View-2 (SeaWiFS)	Harmful algal blooms derived from ocean colour (total suspended matter) data from MERIS, MODIS and SeaWiFS (Kurekin et al. 2014)
Barrier effect of vegetation	Vegetation barriers	Tree cover	Proba V (Vegetation)	Proba V Fraction of green vegetation Cover
	Air quality	Aerosol particles	HyspIRI (VSWIR/TIR)	HyspIRI carbon and dust on snow/ice
Supporting habitats	Habitat extent	Land cover	Sentinel 1 (SAR), Sentinel 2 (MSI), Sentinel 3 (OLCI & SLSTR)	Sentinel Land cover
		Tree Cover	Proba V (Vegetation)	Proba V Fraction of green vegetation Cover
		Vertical vegetation structure	ICESat-2 (ATLAS) or GEDI (HOMER)	LiDAR vertical structure
		Water body distribution	Proba V (Vegetation)	Proba V Water Bodies product
		Sea ice	ENVISAT (ASAR)	ENVISAT ice thickness
			ICESat-2 (ATLAS)	IceSat-2 ice thickness
		Glaciers	Sentinel 2 (MSI)	Sentinel-2 Glacier area, LSSIA and snowline
			Sentinel 1 (SAR)	Sentinel-1 glacier surface topography
		Snow cover	Sentinel 3 (SLSTR, OLCI)	Snow Cover Area Global
	Habitat quality	Albedo	Sentinel 3 (SLSTR, OLCI)	Surface albedo
			Sentinel 2 (MSI)	Surface albedo
			Proba V (Vegetation)	Surface albedo
		Primary productivity	EnMAP (VNIR/SWIR)	EnMAP terrestrial and aquatic phenology
		Vegetation condition	Proba V (Vegetation)	Proba V vegetation condition index
Food	Production of vegetal biomass	Vegetation indices	Proba V (Vegetation)	Proba V FPAR
			Sentinel 2 (MSI), Sentinel 3 (OLCI, SLSTR)	Sentinel 2 and 3 fPAR
			Proba V (Vegetation)	Proba V LAI
			Sentinel 2 (MSI), Sentinel 3 (OLCI, SLSTR)	Sentinel 2 and 3 Chlorophyll and Leaf Area Index (LAI)
		Biomass	Sentinel 1 (SAR)	Sentinel 1 biomass
Raw materials	Wood and NTFP	Tree cover	Proba V (Vegetation)	Proba V Fraction of green vegetation cover
	Mineral resources	Mineral resources	HyspIRI (VSWIR/TIR)	HyspIRI surface mineral resources
Water supply	Water provision	Evapotranspiration	HyspIRI (VSWIR/TIR)	HyspIRI evapotranspiration
		Water body distribution	Proba V (Vegetation)	Proba V Water Bodies product

(*Continued*)

Table 4. Continued.

Function	Indicator	Proxy	Satellite (sensor)	SRS data product
	Water quality	SRS-based estimates of water quality	EnMAP (VNIR/SWIR)	EnMAP water quality and availability
Provision of shade and shelter	Extent to which vegetation shades the ground	Tree cover	Proba V (Vegetation)	Proba V Fraction of green vegetation Cover
		Plant canopy	Sentinel 2 (MSI)	Sentinel 2 Leaf Area Index

ASAR, Advanced Synthetic Aperture Radar; ATLAS, Advanced Topographic Laser Altimeter System; CCI, Climate Change Initiative; CERES, Clouds and the Earth's Radiant Energy System; EnMAP, Environmental Mapping and Analysis Program; ENVISAT, Environmental Satellite; ESA, European Space Agency; ETM+, Enhanced Thematic Mapper Plus; FLEX, Fluorescence Explorer; FLORIS, FLuORescence Imaging Spectrometer; GEDI, Global Ecosystem Dynamics Investigation; HOMER, High Output Maximum Efficiency Resonator; HRG, High Resolution Geometric; HRV, High Resolution Visible; HRVIR, High Resolution Visible and Infrared; HyspIRI, Hyperspectral Infrared Imager; MODIS, Moderate Resolution Imaging Spectroradiometer; MSI, Multispectral Instrument; NOAA, National Oceanic and Atmospheric Administration; OLCI, Ocean and Land Colour Instrument; OLI, Operational Land Imager; PR, Precipitation Radar; SAR, Synthetic Aperture Radar; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; SLSTR, Sea and Land Surface Temperature Radiometer; SPOT, Satellite Pour l'Observation de la Terre; SWIR, Short Wave Infrared; TIR, Thermal Infrared Radiometer; TM, Thematic Mapper; TMI, TRMM Microwave Imager; TRMM, Tropical Rainfall Measuring Mission; VGT, Vegetation; VIRS, Visible and Infrared Scanner; VNIR, Visible and Near Infra-red; VSWIR, Visible to Short Wavelength InfraRed.

areas such as coastal waters and the seabed (Tilstone et al. 2017). Remote sensing products are moreover unlikely to fill all of the needs of conservation decision-makers, scientific research, and environmental assessment focused on tracking or improving ecosystem function, because these needs are defined at different spatial and temporal extents and resolutions, and come with differences in expectations. Given that most data collected to track ecosystem functions will be surrogates (whether it be remotely-sensed, gathered through on-ground monitoring programs, or a combination of both), assessing and acknowledging the expected benefits and limitations of the measured quantity, in terms of accuracy, representativeness, cost, and sensitivity will ultimately be key (Lindenmayer et al. 2015).

The list of satellite remote sensing products relevant to monitoring ecosystem function is likely to change rapidly as efforts to integrate ecosystem function in ecosystem assessments increase, knowledge and technology advances, and costs of data access and processing diminish. Consequently, product users could struggle to maintain an up-to-date knowledge of available data and tools, and decide on how to best derive trends from datasets generated by sensors covering different periods and that have different specifications. To improve on the use of satellite remote sensing data to monitor ecosystem functions, and fully capitalize on current and future opportunities, will require the sharing of information between data providers, ecologists, ecosystem modellers and remote sensing experts interested in ecosystem function monitoring. For this to happen, a clear and common platform for discussion and communication of data products urgently needs to be identified, with well-defined terminology, conceptual translation across disciplines, provision for data sharing and version controls, and communication of the development and capabilities of relevant new technologies. To make such a platform a reality requires identifying who will take responsibility for (i) developing the platform; (ii) updating the information provided on a regular basis, (iii) managing and optimizing engagement with potential users and (iv) securing its viability in the long term. It also requires consistent and continuing funding being allocated to the development and maintenance of such a platform. Such interdisciplinary communication actions may benefit from lessons learned through similar efforts across these communities, e.g. ecosystem model development (Queirós et al. 2015).

The use of satellite remote sensing data to monitor ecosystem functions necessitates practical and/or theoretical training, particularly related to ecology and the geophysical sciences, as well as knowledge in remote sensing; yet few ecologists and conservation biologists typically receive this type of training (Cabello et al. 2012; Pettorelli et al. 2014). Conceptual models of ecosystem functions are a possible nexus of ecosystem process and remote sensing expertise (see Fig. 2), similar to and/or informed by the conceptual ecosystem models developed as part of Red List of Ecosystems assessments (Bland et al. 2016). Potential differences in the conceptual understanding of causality in the drivers of ecosystem processes across disciplines may in this way become apparent, and clarity of understanding promoted across different foci of expertise. By making the variables underpinning ecosystem functions and the relationships between them explicit, such models can help identify a minimum set of agreed variables needed to monitor a given ecosystem function. Opportunities for monitoring these variables via remote sensing could then be systematically identified, focussing on user needs, and gaps in monitoring capacity prioritized. Ultimately, without common references and definitions, and centralized, jointly developed platforms such as these, rapid advances are unlikely.

Policy Implications

In 2011, parties of the CBD adopted a strategic plan for the period until 2020 based on 20 targets of which two address the conservation (Target 11) and restoration (Target 15) of ecosystems services, whose monitoring partially relies on ecosystem function monitoring (Fig. 1). Currently, very little information on the state of ecosystem functions and services is available from the Biodiversity Indicators Partnership, a global initiative to promote and coordinate the development and delivery of biodiversity indicators for use by the CBD and other biodiversity-related conventions, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the Sustainable Development Goals and national and regional agencies. While satellite remote sensing could help track progress towards the CBD targets on ecosystems services (Secades et al. 2014), considerations have so far been limited to carbon and water-based ecosystem services. Satellite applications to the monitoring of ecosystem function and services are also exceptionally well placed to support the achievement of Target 14. A of the United Nations Sustainable Development Goal 14, aimed at the development of research capacity and transfer of marine technology in support of ocean health and the development of nations reliant on living marine resources. But achievement of the aims of the Sustainability Agenda under the United Nations system are currently heavily focused on regional cooperation for data acquisition in support of development policies, and improving access to technology by developing nations.

Focusing on the use of satellite remote sensing to monitor ecosystem functions and deconstructing these into ecological and ecosystem processes should help identify the processes to be monitored and greatly ease the design of the more complex models required to assess the societal benefits underpinned by biodiversity. There is a growing push towards use of ecosystem accounting in policy development and economic analysis from the United Nations Statistical Commission. Similarly, the European Union's first priority objective of the 7th Environment Action Programme to 2020 is to protect, conserve and enhance the Union's natural capital, further highlighting the need to integrate economic indicators with environmental and social indicators, including by means of natural capital accounting (European Commission 2017). This accounting approach would measure changes in the stock of natural capital at a variety of scales and integrate the value of ecosystem services into accounting and reporting systems at the European Union and national levels. It should be seen as a tool supporting the mainstreaming of biodiversity in economic decision-making.

An integrated system for natural capital and ecosystem services accounting is currently in development by the European Union (DG ENV 2015) to explicitly account for the range of ecosystem services and demonstrate in monetary terms the benefits of investing in nature and the sustainable management of resources, allowing assessment of benefits beyond growth of domestic product. Such an integrated accounting system is designed as a shared platform of linked data sets and tools for covering georeferenced information on ecosystems and their services. It will allow assessment of ecosystems' economic importance and value, which can be linked to standard national accounts. It includes layers of data based on (i) earth observation (e.g. land cover), (ii) statistical collections including physical data about human activities (e.g. land use, industrial use), biomass production, water use and availability, (iii) environmental monitoring data including data reported under relevant legislation and (iv) models that quantify ecosystem services such as water, air and soil regulation, pollination, carbon release and sequestration. Here again, providing a clear way for satellite remote sensing to help characterize ecosystem functions would not only allow identification and design of the products that would fit such a system, but the approach itself would greatly ease the identification of the different variables required by the platform when providing quantitative assessments with documented uncertainties.

Conclusions

With a policy agenda increasingly focused on ecosystem service provision (Perrings et al. 2010), understanding the ecology of ecosystem functioning and its implications for the delivery of ecosystem services has never been more important. This contribution both provides a theoretical framework that articulates clear monitoring aims and delivers a list of globally available, standardized remote sensing data sets that relates to ecosystem function monitoring. The structured approach we propose here is particularly important given the ongoing evolution of remote sensing technologies and data availability, and can help progress multiple initiatives (such as the EBV process or the integrated system for natural capital and ecosystem services accounting) aimed at improving global biodiversity monitoring and supporting global conservation targets. This contribution is also intended to catalyse a much needed discussion on how best to capitalize on current and future opportunities associated with satellite remote sensing for monitoring ecosystem functions.

References

Alroy, J. 2015. Current extinction rates of reptiles and amphibians. *Proc. Natl Acad. Sci.* **112**, 13003–13008.

Bengtsson, J. 1998. Which species? What kind of diversity? Which ecosystem function? Some problems in studies of relations between biodiversity and ecosystem function. *Appl. Soil Ecol.* **10**, 191–199.

Berryman, A. A. 2002. Population: a central concept for ecology? *Oikos* **97**, 439–442.

Bland, L. M., D. A. Keith, R. M. Miller, N. J. Murray, and J. P. Rodríguez, eds. 2016. *Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria, Version 1.0*. Pp. ix + 94. IUCN, Gland, Switzerland.

Boero, F., and E. Bonsdorff. 2007. A conceptual framework for marine biodiversity and ecosystem functioning. *Mar. Ecol.* **28**, 134–145.

Braunisch, V., G. Segelbacher, and A. H. Hirzel. 2010. Modelling functional land-scape connectivity from genetic population structure: a new spatially explicit approach. *Mol. Ecol.* **19**, 3664–3678.

Brown, T. C., J. C. Bergstrom, and J. B. Loomis. 2007. Defining, valuing and providing ecosystem goods and services. *Nat. Res. J.* **47**, 329–376.

Brown, M. E., S. D. Arias, T. Neumann, M. F. Jasinski, P. Posey, G. Babonis, et al. 2016. Applications for ICESat-2 data: from NASA's early adopter program. *IEEE Geosci. Remote Sens. Mag.* **4**, 24–37.

Buchhorn, M., D. A. Walker, B. Heim, M. K. Raynolds, H. E. Epstein, and M. Schwieder. 2013. Ground-based hyperspectral characterization of Alaska tundra vegetation along environmental gradients. *Remote Sens.* **5**, 3971–4005.

Cabello, J., N. Fernandez, D. Alcaraz-Segura, C. Oyonarte, G. Pineiro, A. Altesor, et al. 2012. The ecosystem functioning dimension in conservation: insights from remote sensing. *Biodivers. Conserv.* **21**, 3287–3305.

Callicott, J. B., L. B. Crowder, and K. Mumford. 1999. Current normative concepts in conservation. *Conserv. Biol.* **13**, 22–35.

Camargo-Sanabria, A. A., E. Mendoza, R. Guevara, M. Martínez-Ramos, and R. Dirzo. 2015. Experimental defaunation of terrestrial mammalian herbivores alters tropical rainforest understorey diversity. *Proc. R. Soc. Lond. B Biol. Sci.* **282**, 20142580.

Cardinale, B. J., J. E. Duffy, A. Gonzalez, D. U. Hooper, C. Perrings, P. Venail, et al. 2012. Biodiversity loss and its impact on humanity. *Nature* **486**, 59–67.

Carniello, L., S. Silvestri, M. Marani, A. D'Alpaos, V. Volpe, and A. Defina. 2014. Sediment dynamics in shallow tidal basins: *in situ* observations, satellite retrievals, and numerical modeling in the Venice Lagoon. *J. Geophys. Res., series F* **119**, 802–815.

Ceballos, G., P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle, and T. M. Palmer. 2015. Accelerated modern human–induced species losses: entering the sixth mass extinction. *Sci. Adv.* **1**, e1400253.

Chambers, J. Q., G. P. Asner, D. C. Morton, L. O. Anderson, S. S. Saatchi, F. D. Espírito-Santo, et al. 2007. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends Ecol. Evol.* **22**, 414–423.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260.

Cudahy, T., M. Caccetta, M. Thomas, R. Hewson, M. Abrams, M. Kato, et al. 2016. Satellite-derived mineral mapping and monitoring of weathering, deposition and erosion. *Sci. Rep.* **6**, 23702.

Culman, S. W., A. Young-Mathews, A. D. Hollander, H. Ferris, S. Sánchez-Moreno, A. T. O'Geen, et al. 2010. Biodiversity is associated with indicators of soil ecosystem functions over a landscape gradient of agricultural intensification. *Landscape Ecol.* **25**, 1333–1348.

Daily, G. C. 1997. *Nature's services: societal dependence on natural ecosystems*. Island, Washington, DC.

Daily, G. C., S. Polasky, J. Goldstein, P. M. Kareiva, H. A. Mooney, L. Pejchar, et al. 2009. Ecosystem services in decision making: time to deliver. *Front. Ecol. Environ.* **7**, 21–28.

De Groot, R. S., M. A. Wilson, and R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ.* **41**, 393–408.

DG ENV. 2015. http://ted.europa.eu/udl?uri=TED:NOTICE:64198-2015:TEXT:EN:HTML accessed 27/3/2017.

Dominati, E., M. Patterson, and A. Mackay. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol. Econ.* **69**, 1858–1868.

Drever, M., K. Aitken, A. Norris, and K. Martin. 2008. Woodpeckers as reliable indicators of bird richness, forest health and harvest. *Biol. Cons.* **141**, 624–634.

Duncan, C., J. R. Thompson, and N. Pettorelli. 2015. The quest for a mechanistic understanding of biodiversity-ecosystem services relationships. *Proc. R. Soc. B* **282**, 20151348.

Enßle, F., J. Heinzel, and B. Koch. 2014. Accuracy of vegetation height and terrain elevation derived from ICESat/GLAS in forested areas. *Int. J. Appl. Earth Obs. Geoinf.* **31**, 37–44.

European Commission. 2017. http://ec.europa.eu/environment/nature/capital_accounting/index_en.htm. Accessed 28/3/2017.

Fassnacht, F. E., H. Latifi, A. Ghosh, P. K. Joshi, and B. Koch. 2014. Assessing the potential of hyperspectral imagery to map bark beetle-induced tree mortality. *Remote Sens. Environ.* **140**, 533–548.

Fisher, B., R. K. Turner, and P. Morling. 2009. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* **68**, 643–653.

Fuentes, D. A., J. A. Gamon, Y. Cheng, H. C. Claudio, H. L. Qiu, Z. Mao, et al. 2006. Mapping carbon and water vapor fluxes in a chaparral ecosystem using vegetation indices derived from AVIRIS. *Remote Sens. Environ.* **103**(3), 312–323.

Fuhlendorf, S. D., W. C. Harrell, D. M. Engle, R. G. Hamilton, C. A. Davis, and D. M. Leslie. 2006. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. *Ecol. Appl.* **16**, 1706–1716.

Gao, F., J. Masek, M. Schwaller, and F. Hall. 2006. On the blending of the Landsat and MODIS surface reflectance: predicting daily Landsat surface reflectance. *IEEE Trans. Geosci. Remote Sens.* **44**, 2207–2218.

Geijzendorffer, I. R., and P. K. Roche. 2013. Can biodiversity monitoring schemes provide indicators for ecosystem services? *Ecol. Ind.* **33**, 148–157.

Guanter, L., H. Kaufmann, K. Segl, S. Chabrillat, S. Förster, C. Rogass, et al. 2015. The EnMAP spaceborne imaging spectroscopy mission for Earth Observation. *Remote Sens.* **7**, 8830–8857.

Guzy, M., K. Richardson, and J. G. Lambrinos. 2015. A tool for assisting municipalities in developing riparian shade inventories. *Urban For. Urban Green.* **14**, 345–353.

Haines-Young, R., M. Potschin, and F. Kienast. 2012. Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. *Ecol. Ind.* **21**, 39–53.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, et al. 2008. A global map of human impact on marine ecosystems. *Science* **319**, 948–952.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* **342**:850–853.

Hantson, S., S. Pueyo, and E. Chuvieco. 2015. Global fire size distribution is driven by human impact and climate. *Glob. Ecol. Biogeogr.* **24**, 77–86.

Harrison, R. D., S. Tan, J. B. Plotkin, F. Slik, M. Detto, T. Brenes, et al. 2013. Consequences of defaunation for a tropical tree community. *Ecol. Lett.* **16**, 687–694.

Harrison, P. A., P. M. Berry, G. Simpson, J. R. Haslett, M. Blicharska, M. Bucur, et al. 2014. Linkages between biodiversity attributes and ecosystem services: a systematic review. *Ecosyst. Serv.* **9**, 191–203.

Harvey, E. T., S. Kratzer, and P. Philipson. 2015. Satellite-based water quality monitoring for improved spatial and temporal retrieval of chlorophyll-a in coastal waters. *Remote Sens. Environ.* **158**, 417–430.

Harwood, T. D., R. J. Donohue, K. J. Williams, S. Ferrier, T. R. McVicar, G. Newell, et al. 2016. Habitat Condition Assessment System: a new way to assess the condition of natural habitats for terrestrial biodiversity across whole regions using remote sensing data. *Methods Ecol. Evol.* **7**, 1050–1059.

Hilker, T., M. A. Wulder, N. C. Coops, N. Seitz, J. C. White, F. Gao, et al. 2009. Generation of dense time series synthetic Landsat data through data blending with MODIS using a spatial and temporal adaptive reflectance fusion model. *Remote Sens. Environ.* **113**, 1988–1999.

Huang, C., X. Wang, H. Yang, Y. Li, Y. Wang, X. Chen, et al. 2014. Satellite data regarding the eutrophication response to human activities in the plateau lake Dianchi in China from 1974 to 2009. *Sci. Total Environ.* **485**, 1–11.

Huang, X., J. Deng, X. Ma, Y. Wang, Q. Feng, X. Hao, et al. 2016. Spatiotemporal dynamics of snow cover based on multi-source remote sensing data in China. *Cryosphere* **10**, 2453.

Hyde, P., R. Nelson, D. Kimes, and E. Levine. 2007. Exploring LiDAR–RaDAR synergy—predicting aboveground biomass in a southwestern ponderosa pine forest using LiDAR, SAR and InSAR. *Remote Sens. Environ.* **106**, 28–38.

Jansen, P. A., H. C. Muller-Landau, and S. J. Wright. 2010. Bushmeat hunting and climate: an indirect link. *Science* **327**, 30.

Jin, M., and R. E. Dickinson. 2010. Land surface skin temperature climatology: benefitting from the strengths of satellite observations. *Environ. Res. Lett.* **5**, 044004.

Kehinde, T., and M. J. Samways. 2012. Endemic pollinator response to organic vs. conventional farming and landscape context in the Cape Floristic Region biodiversity hotspot. *Agric. Ecosyst. Environ.* **146**, 162–167.

Keith, D. A., J. P. Rodríguez, T. M. Brooks, M. A. Burgman, E. G. Barrow, L. Bland, et al. 2015. The IUCN Red List of Ecosystems: motivations, challenges and applications. *Conserv. Lett.* **8**, 214–226.

Kollmann, J., S. T. Meyer, R. Bateman, T. Conradi1, M. M. Gossner, M. Jr de Souza Mendonça, et al. 2016. Integrating ecosystem functions into restoration ecology—recent advances and future directions. *Restor. Ecol.* **24**:722–730.

Koschke, L., C. Fuerst, S. Frank, and F. Makeschin. 2012. A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecol. Ind.* **21**, 54–66.

Kumar, P. 2010. *The economics of ecosystems and biodiversity: ecological and economic foundations*. Earthscan, London and Washington DC.

Kurekin, A. A., P. I. Miller, and H. J. Van der Woerd. 2014. Satellite discrimination of Karenia mikimotoi and Phaeocystis harmful algal blooms in European coastal waters: merged classification of ocean colour data. *Harmful Algae* **31**, 163–176.

Lamarque, P., F. Quetier, and S. Lavorel. 2011. The diversity of the ecosystem services concept and its implications for their assessment and management. *C.R. Biol.* **334**, 441–449.

Lawton, J. H., and V. K. Brown. 1993. Redundancy in ecosystems. Pp. 255–270 *in* E. D. Schulze and H. A. Mooney, eds. *Biodiversity and ecosystem function*. Springer, New York.

Lefsky, M. A. 2010. A global forest canopy height map from the Moderate Resolution Imaging Spectroradiometer and the Geoscience Laser Altimeter System. *Geophys. Res. Lett.* **37**, L15401.

Likens, G. E. 1992. *The ecosystem approach: its use and abuse*. Ecology Institute, Oldendorf, Luhe.

Lindenmayer, D., J. Pierson, P. Barton, M. Beger, C. Branquinho, A. Calhoun, et al. 2015. A new framework for selecting environmental surrogates. *Sci. Total Environ.* **538**, 1029–1038.

Liu, G., A. E. Strong, and W. Skirving. 2003. Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. *Eos.* **84**, 137–141.

Lovett, G. M., C. G. Jones, M. G. Turner, and K. C. Weathers. 2006. Ecosystem function in heterogeneous landscapes. Pp. 1–4 *in* G. M. Lovett, C. G. Jones, M. G. Turner and K. C. Weathers, eds. *Ecosystem function in heterogeneous landscapes*. Springer, New York.

Mace, G. M., K. Norris, and A. H. Fitter. 2012. Biodiversity and ecosystem services: a multi-layered relationship. *Trends Ecol. Evol.* **27**, 19–26.

Magurran, A. 2004. *Measuring biological diversity*. Blackwell, Oxford.

Mallet, J. 1995. A species definition for the modern synthesis. *Trends Ecol. Evol.* **10**, 294–299.

Malmstrom, C. M., H. S. Butterfield, C. Barber, B. Dieter, R. Harrison, J. Qi, et al. 2009. Using remote sensing to evaluate the influence of grassland restoration activities on ecosystem forage provisioning services. *Restor. Ecol.* **17**, 526–538.

Martinez, N. D. 1996. Defining and measuring functional aspects of biodiversity. Pp. 114–148 *in* K. J. Gaston, ed. *Biodiversity: a biology of numbers and difference*. Blackwell Science, Oxford.

McCauley, D. J., M. L. Pinsky, S. R. Palumbi, J. A. Estes, F. H. Joyce, and R. R. Warner. 2015. Marine defaunation: animal loss in the global ocean. *Science* **347**, 1255641–1255641.

McNaughton, S. J., M. Oesterheld, D. A. Frank, and K. J. Williams. 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. *Nature* **341**, 142–144.

Meyer, S. T., C. Koch, and W. W. Weisser. 2015. Towards a standardized Rapid Ecosystem Function Assessment (REFA). *Trends Ecol. Evol.* **30**, 390–397.

Milchunas, D. T., and W. K. Lauenroth. 1995. Inertia in plant community structure: state changes after cessation of nutrient-enrichment stress. *Ecol. Appl.* **5**, 452–458.

Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: biodiversity synthesis*. World Resources Institute, Washington, DC.

Moretti, M., and C. Legg. 2009. Combining plant and animal traits to assess community functional responses to disturbance. *Ecography* **32**, 299–309.

Nagendra, H., R. Lucas, J. P. Honrado, R. H. Jongman, C. Tarantino, M. Adamo, et al. 2013. Remote sensing for conservation monitoring: assessing protected areas, habitat extent, habitat condition, species diversity and threats. *Ecol. Ind.* **33**, 45–59.

Nelson, R. F., P. Hyde, P. Johnson, B. Emessiene, M. L. Imhoff, R. Campbell, et al. 2007. Investigating RaDAR–LiDAR synergy in a North Carolina pine forest. *Remote Sens. Environ.* **110**, 98–108.

Noss, R. F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conserv. Biol.* **4**, 355–364.

Odum, E. P. 1969. The strategy of ecosystem development: an understanding of ecological succession provides a basis for resolving man's conflict with nature. *Science* **164**, 262–270.

Oliver, T. H., M. S. Heard, N. J. B. Isaac, D. B. Roy, D. Procter, F. Eigenbrod, et al. 2015. Biodiversity and resilience of ecosystem functions. *Trends Ecol. Evol.* **30**, 673–684.

Osuri, A. M., J. Ratnam, V. Varma, P. Alvarez-Loayza, J. H. Astaiza, M. Bradford, et al. 2016. Contrasting effects of defaunation on aboveground carbon storage across the global tropics. *Nat. Commun.* **7**, 11351.

Pacala, S., and A. P. Kinzig. 2002. Introduction to theory and the common ecosystem model. Pp. 169–174 *in* A. P. Kinzig, S. W. Pacala and D. Tilman, eds. *Functional consequences of biodiversity: empirical progress and theoretical extensions*. Princeton Univ. Press, Princeton, NJ.

Paganini, M., A. K. Leidner, G. Geller, W. Turner, and M. Wegmann. 2016. The role of space agencies in remotely sensed essential biodiversity variables. *Remote Sens. Ecol. Conserv.* **2**, 132–140.

Paterson, D. M., E. C. Defew, and J. Jabour. 2012. Ecosystem function and co-evolution of terminology in marine science and management. Pp. 24–33 *in* M. Solan, R. J. Aspden and D. M. Paterson, eds. *Marine biodiversity and ecosystem functioning*, 1st ed.. Oxford University Press, Oxford.

Patterson, P. L., and S. Healey. 2015. Global ecosystem dynamics investigation (GEDI) LiDAR sampling strategy. P.

245 in S. M. Stanton, G. A. Christensen, eds. *Pushing boundaries: new directions in inventory techniques and applications: Forest Inventory and Analysis (FIA) symposium 2015*. 2015 December 8–10; Portland, Oregon. Gen. Tech. Rep. PNW-GTR-931. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Peng, Y., R. B. Kheir, K. Adhikari, R. Malinowski, M. B. Greve, M. Knadel, et al. 2016. Digital mapping of toxic metals in Qatari soils using remote sensing and ancillary data. *Remote Sens.* **8**, 1003.

Pereira, H. M., S. Ferrier, M. Walters, G. N. Geller, R. H. G. Jongman, R. J. Scholes, et al. 2013. Essential biodiversity variables. *Science* **339**, 277–278.

Peres, C. A., T. Emilio, J. Schietti, S. J. Desmoulière, and T. Levi. 2016. Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *Proc. Natl Acad. Sci.* **113**, 892–897.

Perrings, C., S. Naeem, F. Ahrestani, D. E. Bunker, P. Burkill, G. Canziani, et al. 2010. Ecosystem services for 2020. *Science* **330**, 323–324.

Petter, M., S. Mooney, S. M. Maynard, A. Davidson, M. Cox, and I. Horosak. 2012. A methodology to map ecosystem functions to support ecosystem services assessments. *Ecol. Soc.* **18**:31. http://dx. doi.org/https://doi.org/10.5751/ES-05260-180131.

Pettorelli, N. 2013. *The normalized difference vegetation index*. Oxford University Press, Oxford.

Pettorelli, N., W. F. Laurance, T. G. O'Brien, M. Wegmann, H. Nagendra, and W. Turner. 2014. Satellite remote sensing for applied ecologists: opportunities and challenges. *J. Appl. Ecol.* **51**, 839–848.

Pettorelli, N., M. Wegmann, A. Skidmore, S. Mücher, T. P. Dawson, M. Fernandez, et al. 2016. Framing the concept of Satellite Remote Sensing Essential Biodiversity variables: challenges and future directions. *Remote Sens. Ecol. Conserv.* **2**, 122–131.

Puri, S., H. Stephen, and S. Ahmad. 2011. Relating TRMM precipitation radar backscatter to water stage in wetlands. *J. Hydrol.* **401**, 240–249.

Queirós, A. M., S. N. Birchenough, J. Bremner, J. A. Godbold, R. E. Parker, A. Romero-Ramirez, et al. 2013. A bioturbation classification of European marine infaunal invertebrates. *Ecol. Evol.* **3**, 3958–3985.

Queirós, A. M., J. Bruggeman, N. Stephens, Y. Artioli, M. Butenschön, J. C. Blackford, et al. 2015. Placing biodiversity in ecosystem models without getting lost in translation. *J. Sea Res.* **98**, 83–90.

Racault, M.-F., T. Platt, S. Sathyendranath, E. Ağirbaş, V. Martinez Vicente, and R. Brewin. 2014. Plankton indicators and ocean observing systems: support to the marine ecosystem state assessment. *J. Plankton Res.* **36**, 621–629.

Ribeiro, I. O., R. A. F. de Souza, R. V. Andreoli, M. T. Kayano, and P. dos Santos Costa. 2016. Spatiotemporal variability of methane over the Amazon from satellite observations. *Adv. Atmos. Sci.* **33**, 852–864.

Roe, D., J. Elliott, C. Sandbrook, and M. Walpole. 2013. Linking biodiversity conservation and poverty alleviation: what, why and where? Pp. 3–18 *in* D. Roe, J. Elliot, C. Sandbrook and M. Walpole, eds. *Biodiversity conservation and poverty alleviation: exploring the evidence for a link*. John Wiley & Sons, Chichester.

Schlerf, M., C. Atzberger, J. Hill, H. Buddenbaum, W. Werner, and G. Schüler. 2010. Retrieval of chlorophyll and nitrogen in Norway spruce (*Picea abies* L. Karst.) using imaging spectroscopy. *Int. J. Appl. Earth Obs. Geoinf.* **12**, 17–26.

Schmidt, M., R. Lucas, P. Bunting, J. Verbesselt, and J. Armston. 2015. Multi-resolution time series imagery for forest disturbance and regrowth monitoring in Queensland, Australia. *Remote Sens. Environ.* **158**, 156–168.

Schröter, M., C. Albert, A. Marques, W. Tobon, S. Lavorel, J. Maes, et al. 2016. National ecosystem assessments in Europe: a review. *Bioscience* **66**, 813–828.

Schulp, C. J., and R. Alkemade. 2011. Consequences of uncertainty in global-scale land cover maps for mapping ecosystem functions: an analysis of pollination efficiency. *Remote Sens.* **3**, 2057–2075.

Secades, C., B. O'Connor, C. Brown, and M. Walpole. 2014. Earth Observation for Biodiversity Monitoring: A review of current approaches and future opportunities for tracking progress towards the Aichi Biodiversity Targets. Secretariat of the Convention on Biological Diversity, Montréal, Canada. Technical Series No. 72.

Semmens, K. A., M. C. Anderson, W. P. Kustas, et al. 2016. Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sens. Environ.* **185**, 155.

Senay, G. B., N. M. Velpuri, H. Alemu, S. M. Pervez, K. O. Asante, G. Kariuki, et al. 2013. Establishing an operational waterhole monitoring system using satellite data and hydrologic modelling: application in the pastoral regions of East Africa. *Pastoralism*, **3**:20.

Skidmore, A. K., N. Pettorelli, N. C. Coops, G. N. Geller, M. Hansen, R. Lucas, et al. 2015. Agree on biodiversity metrics to track from space. *Nature* **523**, 403–405.

Solan, M., B. J. Cardinale, A. L. Downing, K. A. M. Engelhardt, J. L. Ruesink, and D. S. Srivastava. 2004. Extinction and ecosystem function in the marine benthos. *Science* **306**, 1177–1180.

Spera, S. A., G. L. Galford, M. T. Coe, M. N. Macedo, and J. F. Mustard. 2016. Land use change affects water recycling in Brazil's last agricultural frontier. *Glob. Change Biol.* **22**, 3405–3413.

Spichtinger, N., M. Wenig, P. James, T. Wagner, U. Platt, and A. Stohl. 2001. Satellite detection of a continental scale plume of nitrogen oxides from boreal forest fires. *Geophys. Res. Lett.* **28**, 4579–4582.

Spruce, J. P., S. Sader, R. E. Ryan, J. Smoot, P. Kuper, K. Ross, et al. 2011. Assessment of MODIS NDVI time series data products for detecting forest defoliation by gypsy moth outbreaks. *Remote Sens. Environ.* **115**, 427–437.

Srivastava, D. S., and M. Vellend. 2005. Biodiversity-ecosystem function research: is it relevant to conservation? *Annu. Rev. Ecol. Evol. Syst.* **36**, 267–294.

Steenweg, R., M. Hebblewhite, R. Kays, J. Ahumada, J. T. Fisher, C. Burton, et al. 2017. Scaling-up camera traps: monitoring the planet's biodiversity with networks of remote sensors. *Front. Ecol. Environ.* **15**, 26–34.

Stephens, P., N. Pettorelli, J. Barlow, M. Whittingham, and M. Cadotte. 2015. Management by proxy? The use of indices in applied ecology. *J. Appl. Ecol.* **52**, 1–6.

TEEB. 2010. *The economics of ecosystems and biodiversity: ecological and economic foundations*. Earthscan, London and Washington.

Thompson, D. R., I. Leifer, H. Bovensmann, M. Eastwood, M. Fladeland, C. Frankenberg, et al. 2015. Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane. *Atmos. Meas. Tech.* **8**, 4383–4397.

Tilstone, G., S. Mallor-Hoya, F. Gohin, A. Belo Couto, C. Sá, P. Goela, et al. 2017. Which ocean colour algorithm for MERIS in North West European waters? *Remote Sens. Environ.* **188**, 132–151.

Tong, C., J. Wu, S. Yong, J. Yang, and W. Yong. 2004. A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. *J. Arid Environ.* **59**, 133–149.

Tulloch, A. I. T., P. Sutcliffe, I. Naujokaitis-Lewis, R. Tingley, L. Brotons, K. M. P. M. B. Ferraz, et al. 2016. Conservation planners tend to ignore improved accuracy of modelled species distributions to focus on multiple threats and ecological processes. *Biol. Cons.* **199**, 157–171.

Valente, A. S., and J. C. da Silva. 2009. On the observability of the fortnightly cycle of the Tagus estuary turbid plume using MODIS ocean colour images. *J. Mar. Syst.* **75**, 131–137.

Valiela, I., J. L. Bowen, and J. K. York. 2001. Mangrove Forests: one of the World's Threatened Major Tropical Environments. *Bioscience* **51**, 807–815.

Veraverbeke, S., F. Sedano, S. J. Hook, J. T. Randerson, Y. Jin, and B. M. Rogers. 2014. Mapping the daily progression of large wildland fires using MODIS active fire data. *Int. J. Wildl. Fire* **23**, 655–667.

Vierling, K. T., L. A. Vierling, W. A. Gould, S. Martinuzzi, and R. M. Clawges. 2008. Lidar: shedding new light on habitat characterization and modeling. *Front. Ecol. Environ.* **6**, 90–98.

Villar, R. E., J. M. Martinez, M. Le Texier, J. L. Guyot, P. Fraizy, P. R. Meneses, et al. 2013. A study of sediment transport in the Madeira River, Brazil, using MODIS remote-sensing images. *J. S. Am. Earth Sci.* **44**, 45–54.

Walker, J. J., K. M. De Beurs, R. H. Wynne, and F. Gao. 2012. Evaluation of Landsat and MODIS data fusion products for analysis of dryland forest phenology. *Remote Sens. Environ.* **117**, 381–393.

Wallace, K. J. 2007. Classification of ecosystem services: problems and solutions. *Biol. Cons.* **139**, 235–246.

Webb, T. J., and B. L. Mindel. 2015. Global patterns of extinction risk in marine and non-marine systems. *Curr. Biol.* **25**, 506–511.

Werling, B. P., T. L. Dickson, R. Isaacs, H. Gaines, C. Gratton, K. L. Gross, et al. 2014. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proc. Natl Acad. Sci.* **111**, 1652–1657.

WWF Living Planet Report. 2016. *Risk and resilience in a new era*. WWF International, Gland, Switzerland.